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We showed this on seven subjects who were tested tachistoscopically for form resolution and identification simultaneously at the center of gaze and at the near peripheral field of vision.

Binocular eye motion as if tracking along the boundary of an object can occur without any visual cognition that there is such an object in the visual field. We showed this on eight subjects who were exposed to random dot stereograms and monitored with a state-of-the-art binocular eye tracker.

Our data led us to believe that measures of eye position and motion are fallible indices of visual cognition. Nevertheless, as in medicine, signs of disorder may be inexplicable yet reliable. Our study leads us to believe that tests can be designed for cognitive fatigue and overload using transient and well-defined visual tasks imposed on the visual field.

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HUMAN COGNITIVE OVERLOAD: PHYSIOLOGICAL AND METHODOLOGICAL TECHNIQUES FOR MEASURING COGNITIVE OVERLOAD

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August 14, 1998

ABSTRACT

The running state of visual cognition cannot be told from the running state of eye motion. Even the simplest and most commonly accepted beliefs fall apart when carefully studied. Visual attention is not confined to the center of gaze but can wander about over the visual field and become narrow or wide depending on the visual task to be performed.

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Our data led us to believe that measures of eye position and motion are fallible indices of visual cognition. Nevertheless, as in medicine, signs of disorder may be inexplicable yet reliable. Our study leads us to believe that tests can be designed for cognitive fatigue and overload using transient and well-defined visual tasks imposed on the visual field.

INTRODUCTION

Eyes do not necessarily move to where attention is directed, nor does attention necessarily center on where the eyes are directed. Much information in the visual field can be processed cognitively with but little eye movement. Furthermore, in earlier studies we have shown that the strategies of that visual process are learned and are task specific, so that there are many such strategies and a viewer can switch between them in ordinary vision depending upon his purpose. We can qualify some of these strategies by our tests. We have shown that they can be learned and that switching between strategies can be learned.

The basic point is that there is no way of telling from the position or motion of the eyes the visual strategy used or the state of visual cognition. The field of attentive and discriminatory vision can widen or constrict and objects can assume distinct individual form or be much degraded in their visual aspects without any external signs that this is occurring.

Accordingly, inferring the laws of vision, visual attention and visual interpretation from the external action of the eyes is not a fruitful scientific pursuit.

However there is a serious practical problem where such study may be implied, and that has to do with the onset of visual fatigue, cognitive overload, or interpretive block. The subjective symptoms are not so noticeable nor are the external signs. But in many occupations the access of blunted visual cognition can have disastrous consequences.

Our experiments suggest that no external measure of the running mechanical activity of the eyes informs us of the running state of visual perception and cognition. However, measured performance of transient well-defined tasks in visual perception gives consistent findings of diagnostic value. This suggests the design of a new kind of test for detecting visual fatigue and cognitive overload.

The test does not interfere with ongoing visually directed operation, but only checks occasionally the capacity to perform a transient well-defined visual task. The design and instrumentation of such a method, and testing it for usefulness compliments our ongoing research.

Tracking eye movement is familiar enough as an instrumental problem. Binocular two-dimension tracking and its broad band recording for detecting rapid fine saccades as well as courser ones are well in hand. Our innovation with regard to this newly refined measure has been to show that there is no intelligible coupling between binocular action and conscious perception or cognition. There may be a general correlation in some crude average way, but certainly not on careful study of task performance. According to the current data, no casual relationship can be established such that we can rely on ocular signs to indicate symptoms of visual cognitive overload or impairment.

The case is different for our method of testing one feature of visual cognition, the FRF (form-resolving field). Since we know from eye-tracking the position of the center of gaze, the question is the position and width of the FRF in the visual field relative to the center of gaze. It is that solid angle in which pairs of forms, such as image objects, icons, letters and their changes can be recognized. Both the width and position of this field with respect to the center of gaze vary depending on the state of the individual, the cognitive task to be performed and the individual strategy of performance.

The method has high diagnostic value in detecting dyslexia, for example. It consists of tachistoscopically presenting two forms against a blank background, one at the center of gaze, the other at some randomly chosen angular distance away from the center. With this test we have shown that we can reliably estimate the angular field in which the paired forms are recognized, and can use the position and width of that field referred to the center of gaze as qualifying the strategy of visual perception in immediate use.

For it is the case that the "spotlight of attention" can expand or constrict and change its center of gaze depending on the cognitional strategy.

This is the test we expect to modify in order to check, in a non-interventive way, the strategic competence of visual perception in, say, a flight controller or a pilot. The stimuli are transient, involve occasional momentary random changes in motion of objects on a screen and identifying the direction and magnitude of such changes. We believe that this relatively simple test, conceptually speaking, will do more to reveal the running visual cognitive competence of an active observer, than would any physical measures on the eyes.

EXPERIMENTAL PROTOCOLS

FIRST PROTOCOL: COMPARING THE FORM-RESOLVING FIELDS (FRF) OF JAGGED AND SMOOTH LETTERS

Methods and Apparatus

Three slide projectors, equipped with flat field lenses and electrically activated shutters (Vincent Associates) back-projected images of letters on a diffusing screen. The arrangement served as a wide-screen tachistoscope. Each of the projectors gave uniform luminance of 210 cd/m +10% across the whole screen. The first projector carried a slide with a central fixation point. The second carried the stimulus slide. The third carried a blank "eraser" slide. The order of presentation of the slides on the screen and the duration of presentation was controlled electronically by a timer. It adjusted the openings and closings of the shutters to minimize transitional changes in luminance on the screen between presentations. Stimulus duration was adjustable over the range of 1.6 ms to 150 ms. The stimulus duration for each subject was individually chosen, as will be explained in the procedure section. The screen was 49 cm wide

and 32 cm high corresponding to 390 of visual angle horizontally and 260 vertically from an observation distance of 69 cm.

Stimuli

Each stimulus slide carried two letters, one in the center at the location of the fixation point and the second in the periphery. The stimuli were divided into 5 groups. In each group the letters in the periphery were at a fixed angular horizontal distance from the fixation point at the center. The angles used were from 2.50 to 12.50 in 2.50 steps. Each group contained 40 slides. In half of them the peripheral letter was to the left of the fixation point and in half to the right (i.e. there were 10 slides at each eccentricity). They were presented in a random order. This procedure helped observers to maintain central fixation and reduced the bias of expectation of appearance (Geiger and Lettvin, 1989, Geiger et al., 1992). The two letters on each stimulus presentation were different, and were chosen from a fixed set of 10 upper-case Helvetica-medium letters (I, S, C, O, V, M, N, E, T, H).

We made two sets of slides of identical letters with identical eccentricities. The difference between the sets was that in one the letters were smooth, as they appear in print and in the other they were jagged as they might appear on a CRT screen. The sets were otherwise identical in their font, size and stroke width. Each letter in a set appeared once at each of the eccentric visual field positions, and twice at the central position. The letter height subtended 35 min of visual arc, and letter contrast was 90%.

Subjects

Seven adult subjects from the university population were measured in this section of the study. Their ages were 22 to 55 years of age. All were ordinary (proficient) readers, and all had normal, or corrected to normal vision.

Procedure

Each subject sat 69 cm away from the screen in a dimly lit room. A fixation point was projected on the screen. The subject was asked to look at the fixation point. Shortly after a verbal warning the stimulus slide was briefly projected (replacing the fixation point slide) and followed by a blank eraser slide which was projected for 2.5 s. The subject was asked to name the letters in the stimulus slide and their relative position. This cycle continued until all 160 stimuli slides had been

presented. The effective stimulus duration, the time between the offset of the fixation point slide and the onset of the eraser slide, was determined for each subject separately prior to the test itself. Various stimulus duration were tested (with samples of the letter pairs) in this pre-test until a stimulus duration was found in which the correct letter identification reached just 100% at one eccentricity of the peripheral letter in the display (this was at 2.50 for all the subjects). Once the appropriate stimulus duration was found it was kept constant during the test and for the subsequent FRF measure. After all stimulus slides were presented the average letter recognition at each eccentricity was calculated and plotted to give the FRF plot. Separate FRF plots were made for the jagged letters and for the smooth letters, and were then compared.

FRF Study Results

The form-resolving field (FRF) is the plot of average correct recognition as a function of eccentricity of the peripheral letters of letter pairs, where one of the letter pairs was at the center of gaze and the other in the periphery along the horizontal line.

Figure 1 depicts the average FRF obtained by presenting smooth letters (solid line) and that of jagged letters (dashed line). As is evident from the figure, jagged letters are recognized better in the periphery than are smooth letters. This difference is statistically significant ($p<0.01$) except at the far left (-12.5 deg). where the difference is not statistically significant. The recognition of the letters at the center of gaze was 100% correct for both letter types.

The average stimulus presentation time was 5.4 ms. (range of 4.5 to 6.5 ms.). As previously mentioned, the stimulus presentation time was determined individually prior to the measurement, and then kept constant throughout the measurements.

We did not measure the jagged letters at 2.5 and 5 deg. distances of the peripheral letters, as this would have made the program of measurement too long to discount fatigue effects on the measurements. However as the recognition of the letter at the center of gaze was equal for all letters we feel that that was a reasonable compromise.

The FRF of blurred letters

In order to exclude the notion that additional higher spatial frequencies in the jagged letter (aliasing) are the reason for the superior recognition in the periphery, we conducted a second

measurement with all letters (smooth and jagged) being blurred by 2 diopters. We achieved the blurring by defocusing the slide projector that projected the letters. The procedure of the measurement was otherwise like that of the previous measurement with the same stimulus presentation duration.

The results were surprising. The recognition of the blurred letters in the periphery (i.e. 7.5 deg and farther away) was similar to that of the distinct letters, for both letter types (as seen in Figure 2 for smooth letters). That is, the superiority of peripheral recognition of the jagged letters over the smooth ones remains also when the letters are blurred, although the higher spatial frequencies are diminished. In addition, smooth letters, either distinct or blurred, are recognized equally well in the periphery, and this holds for the jagged letters as well. (However, the smooth letters, when presented closer to the center, are recognized better when distinct.)

Detecting whether letters are jagged or smooth

The question remained if higher cognitive access, i.e. recognizing the letter type (smooth or jagged), could have influenced recognition. To answer this question we presented the subjects with all the letters, as before, with the same stimulus presentation time, but rearranged their order of presentation. The subject were to tell only if the letters they saw were jagged or smooth, without identifying each letter. The default answer by all the subjects was that the letters were smooth. Only about 7% of the jagged letters were correctly detected as such in the periphery (from about 50% of all letters), however, 22% were correctly identified at the center of gaze.

Discussion of Form Resolving Field Experiments

In order to demonstrate how sensitive the FRF measure is to different visual strategies we demonstrated the difference in the FRF to smooth and to jagged letters. As we demonstrated, recognition of jagged letters is significantly better than smooth letters in the near peripheral visual field. As we also showed, this is not due to aliasing or other cognitive effects due to recognition of the difference in letter types, for that is the outcome of the blurred letter measurement and the experiment on detection. We suggest however, that the difference in recognizing the letter type is due to different visual strategies employed by the subjects when viewing smooth or jagged letters. A crude demonstration in perception is given in Figure 3. When looking at the large (dizzying) print one feels differently than when looking at the smooth smaller print. When moving ones gaze

from one to the other, the individual is most aware of the shift. This difference is not due to the size of the letters, but rather the manner in which they appear.

As we have previously suggested (Geiger et al. 1992), a visual strategy is determined first by the region of distinct vision which is necessary for the accomplishment of the task. This region of distinct vision is in the foreground whereas the remainder, which is not crucial to the task, is in the background, or ambient visual texture. We suggested that what relegates a visual figure to the background is an active masking process (Geiger and Lettvin, 1986, Geiger et al. 1992), which is known in the literature as lateral masking. Lateral masking is the adverse effect on recognition that neighboring visual elements have on each other. A demonstration of lateral masking is presented in figure 4. For additional references on lateral masking see: Bouma 1970, Mackworth 1965, Townsend et al. 1971 and Wolford and Chambers 1983). As can also be seen from the figure demonstrating lateral masking, it reduces a coherent well ordered form to a clumped aggregation of the parts (Geiger et al 1992). Furthermore, we have demonstrated that the FRF measure reflects faithfully the measure of the distribution of lateral masking over the visual field (Geiger and Lettvin 1987, Geiger et al 1992). We also have shown that the distribution of lateral masking changes with the task (Zegarra-Moran and Geiger, 1993).

We demonstrated in our earlier work that a perceptual strategy is learned by practice, and is very specific for the task. That is, one has to learn a new strategy, not simply modify by slight change to an existing one (Geiger and Lettvin, 1987, Geiger et al 1992).

In these terms we suggest that while viewing jagged letters the lateral masking nearer to the center is reduced as compared with viewing smooth letters where lateral masking is more active closer to the center of gaze. To demonstrate the validity of this argument we have shown a string of 3 smooth letters in the near periphery (Figure 5) to 38 persons and asked them to recognize (away from a fixation point) the middle letter in the peripheral string and then did the same with the same letters jagged. In all cases the persons asked found it easier to recognize the middle letter in the string when the letters were jagged.

A remarkable case in point involved an apparent experimental appearance of "fatigue" which was accompanied with radical change of the FRF and task performance is a "conditional dyslexic" person (Geiger et al. 1992). This person was able to read normally and perform similar visual tasks in the morning when "fresh". However, in the afternoon when he was "fatigued" he was

unable to read (only able to skim the text fast and very inaccurately) but was a very able and precise artist using non-textual visual strategies. His FRFs of the morning and afternoon phases are shown in Figure 6. He had readers' FRF in the morning, but in the afternoon he possessed a broad FRF with masking near the center right (which is characteristic to dyslexics) (Geiger and Lettvin, 1987, 1993, Geiger et al 1992) in the fatigued phase.

These sets of measurements demonstrate the task-specific distinctions between visual strategies, and the efficiency of the FRF as a measure to detect such differences.

In the light of these findings and our previous publications, we suggest that any measure for the level of task performance must be specific for each task. We furthermore believe that the FRF or a modified form of it is the appropriate candidate for detecting cognitive overload by detecting the loss of the capacity to continue to perform a specific task at the skill level required.

An additional aspect of our experimental results that demonstrate a wider visual strategy for jagged letters concerns the use of CRT screens. CRT screens (unless they are of the ultra-modern flat screen variety) do not display letters with optically smooth edges. Since CRT displayed characters will be of the jagged variety, this means that the ability to localize ones attention on a CRT screen will be reduced compared with similar visual icons presented optically with smooth edges. That is expressed commonly when proof reading a text. This explains why most editors prefer reading from the print rather than from the CRT screen.

SECOND PROTOCOL: MEASUREMENT OF EYE-MOVEMENTS WHILE OBSERVING RANDOM DOT STEREOGRAMS (RDS)

Methods and Apparatus

Binocular eye-movements of the subjects were recorded with an ET3 eye tracking system (AMTech GmbH) which is a binocular eye-tracker. The technical details of this device are presented in the appendix of this report. The eye-tracker simultaneously records the horizontal and vertical position of each eye separately. These channels allow the plotting of the individual and conjugate action of the eyes in 1 or 2 dimensions. Thus the horizontal vergence response can be retrieved by plotting the running differences of the horizontal positions of both eyes as a function of time.

The horizontal position of each eye was measured 100 times each second, while the vertical position 50 times. At that frequency of recording the eye-tracker had a horizontal spatial resolution of 6 min of arc and a vertical spatial resolution of 18 min. of arc.

An additional two signals were incorporated into the eye-tracker system: that of the stimulus (from begin to end of stimulus presentation), and that of stimulus recognition (or absence of recognition) by the subject. A subject held push-button that was pressed when the form presented was recognized (or partially recognized) indicated stimulus recognition.

On the half mirror of the eye-tracker through which the subject looked, we placed a red filter in front of one eye and a green one in front of the other, in such a way that each eye saw the stimulus by one color only.

Stimuli

The stimuli consisted of different forms incorporated in random dot stereograms (RDS). These stereograms were consisted of two images composed of random dots, one presented in red and the other in green. The random dots in the two halves are identical except for the form to be seen, say a square, where there the dots are shifted slightly (disparate) in position. This disparity is processed by the person's nervous system to be seen as a square surface on a different plane from the rest of the surface of the dot array. The form is perceived by virtue of its apparent depth with respect to the background.

Two slide projectors back projected the two dot arrays of the RDS onto the same location on a semi-translucent screen. In front of one slide projector there was a red filter and a green filter was placed in front of the other. This arrangement gave a crossed disparity when a red filter was in front of the right eye and a green filter in front of the left eye of the subject. The RDS was viewed from the side of the screen opposite to the projectors. The crossed disparity results in the percept of the form being towards the subject. When the color filters in front of the eyes were reversed, the uncrossed disparity gave the percept of the form being further away from the subject.

The size of the screen, the distance of the slide projectors and the distance of the subject from the screen were so arranged to give the stimulus a field of 22.1 deg. of visual arc horizontal and vertical. With that arrangement a dot size (of the RDS) was 3.2 min of visual arc.

There were a few different forms embedded in different stimuli. They were:

- A flat field, where the whole field size was at one or another disparity to give the percept of a large rectangular planar surface.
- A small square (5.5 deg. x 5.5 deg.) in the center.
- A medium size square (8 deg x 8 deg.) in the center.
- A concentric double square in the center, like a two-layered concentric pyramid with a 5.5 x 5.5 deg. square on top of an 8 x 8 deg. square.
- Three stairs from right to left along the height of the field
- A concentric spiral.

Three dots densities were used in different stimuli, namely 5000, 10000 and 20000 dots over the whole field. The contrast of the dots was approximately 50%.

Subjects

Eight adults from the university population were tested. They were 22 to 36 years of age. All the subjects except one had normal stereo vision. The one different was "stereo blind", i.e., he could not perceive the forms presented, even over very long viewing periods. Otherwise, all subjects had normal vision.

Procedure

The subjects were first tested for their stereo vision by viewing the RDS stimuli through the red and green filters but not yet harnessed to the eye-tracker.

After their stereo vision was tested they were asked to look at the screen through the eye-tracker, while the apparatus was adjusted.

Once adjusted, a calibration record was taken. The subject was asked to gaze at 9 successive locations on the screen while the eye-tracker recorded the movements of the eyes. These points consisted of a fixation point along with eight symmetrically arranged dots covering the rest of the field. A third slide projector projected these dots. This record provided a baseline for the horizontal and vertical ocular response to known angular distances.

A second calibration record was conducted for vergence response. The subject's eye-movements were recorded while moving the gaze from the center fixation point on the screen to central closer points, held by an optical bench closer to the subject by 25 cm and 50 cm. These points corresponded to 46 min. of arc and 2 deg of arc changes from the zero position, which is that when the eyes gaze on the fixation point on the screen.

After the calibration records were made for each subject, the recording of eye-movements while viewing RDS began.

At first a fixation point was projected on the screen (projected by the third slide projector). The subject was asked to fix the gaze at that point. Then the recording of the eye-movements began. After 2 seconds the fixation point disappeared and the two half images appeared. The exchange took less than 3 ms. and was controlled by fast electronic shutters. The subject was instructed before the recording to freely move the eyes when presented a stimulus. The stimulus remained on the screen for 10 s. after which the fixation point re-appeared. The onset of the stimulus and its termination was recorded also by the eye-tracker. The subject was given a hand-held push-button at the beginning of the session, and instructed to press it as soon as he or she recognized (or partially recognized) a form. This signal was also recorded by the eye-tracker. When the fixation point re-appeared at the end of stimulus presentation the subject was instructed (before hand) to gaze at that point. This was in order to assure that there was no drift of the device throughout the recording. When the record was concluded, the subject was asked to report the percept, the form seen and whether it appeared towards or away from the subject with respect of the plane of the screen. Following this debriefing, a new stimulus was prepared and a new record made. The records were stored in the eye-tracker's computer for later processing.

Data Processing

Each record was analyzed for the spatial and temporal relations. They included:

- Position detection by the eyes (the instant the saccade comes within 1 deg. of the boundaries of the form). This estimate was made possible, as the location of the form on the screen was known. Due to the calibration record the relative eye-position given by the eye-tracker could be reliably related to the form's location and the location of its contours.
- Vergence response (the instant the horizontal vergence response changes to reach a new steady plane). The horizontal vergence was measured by the difference of the angular horizontal positions of the two eyes. The vergence at the fixation point determines the reference (zero depth). Any change gives either a negative number taken as crossed response (towards the subject) or a positive number taken as an uncrossed response (away from the subject).
- The instant of recognition of the form. (If the form was not recognized throughout the 10 s. of viewing time of the stimulus, that instant was considered to be 10s).

In this way we could determine the temporal differences between the detection by the eyes of the attributes of the forms (position and vergence) separately from the recognition of the form.

As will be presented later, statistical averaging of the time required for detection or recognition was conducted.
In addition, correlations were made for:

- ✓ The form presented with the form perceived.
- ✓ The depth perceived with the actual disparity.
- ✓ The recorded vergence with the actual disparity.
- ✓ The vergence response with the perception of depth.

Results of the Eye-Tracking Experiments

Single Eye-Movement Records

The results from individual eye-movement records were broad in their response. Records showing saccadic eye-movements ranged from one in which the eyes moved to the position of the form's contour accompanied by an appropriate vergence response notwithstanding the fact that the form was not (even partially) recognized by the subject. This response is shown in Figure 7. On the other extreme, another record, presented in Figure 8, shows the eye movements of the same

subject (same session) viewing the same RDS square form as before. In this case, however, the subject recognized the form before any directed saccadic or vergence eye-movements were made. After recognizing the form, the subject's eyes moved to the form's contours and made the appropriate vergence response.

To demonstrate that the saccadic movements of the eyes were not completely random, but had been related to the form's attributes we show two more records in Figures 9 and 10. In these records the stimuli were presented to the same subject (and in the same session) but they were only flat surfaces subtending the whole RDS field which were either closer (Figure 9) or further (Figure 10) from the subject with relation to the plane of the fixation point. It is evident that in both of these records the saccadic eye-movements were very different from the previous records, since there were no form contours present. In these records, as in the previous ones, the vergence response was appropriate.

The eye-movement records have consistently shown that in the presence of contours in the stimuli there were directed saccades towards them (or within a short angular distance from them); similarly, with the vergence response. That allowed us to assume that when the eyes made these movements they "detected" the form's attributes in these stimuli. Once we made this assumption, we could consider the first directed saccade to the contour's position as the instant of detection of the contour's position by the eyes. Similarly with the vergence response. That is, the first instant at which the steady vergence response is in the direction given by the stimulus' disparity, is a sign of correct detection of that disparity.

A short technical remark is appropriate here. In general, when that which is displayed to a subject is abruptly changed (as in our experiments, the change from the fixation point to the RDS stimuli), this change resulted in a -0.5 deg. automatic (reflexive) vergence response, i.e., towards the subject. Once that adjustment reflex response was made the actual zero vergence is then at –0.5 deg. Hence, we took in to account this factor in making the vergence response calculations.

Most of the eye-movement records we measured contained similarities, but varied considerably. We therefore characterized the ensemble of the records with a statistical treatment of the data.

Statistical Analysis of Some Eye-Movement Parameters

As previously mentioned, we calculated 4 correlation factors and 3 different temporal measures from each record. The averages of these measurements are presented in Table 1.

The same letter that appears on top of the respective column in Table 1 indicates the correlations and temporal factors listed here.

These correlations are:

B. The form presented with the form perceived.
C. The depth perceived with the actual disparity.
D. The recorded vergence with the actual disparity.
E. The vergence response with the perception of depth.

When the parameters were in agreement, the response was assigned the numeral 1; when the response signified misperception or that the parameters were in disagreement, the response was assigned the numeral 0.

The temporal factors are:

G. The time taken from the onset of the stimulus to the recognition of the form by the subject.
H. The time taken from the onset of the stimulus until a directed saccade was made to within 1 deg. of the form's contour.
I. The time taken from the onset of the stimulus to a registered steady vergence response.

Discussion

From the data presented, our main argument is that stimulus recognition and eye-movement parameters are poorly correlated, hence eye-movements are a poor measure of cognition.

The RDS records shown in Table 1 demonstrate that only in 66.46% of the records did the subjects recognize the forms embedded in the RDS stimuli. Furthermore, the subjects were able to correctly perceive the depth information embedded in the stimuli only 44.94% of the time. At the same time, the eyes were able to perform 82.91% correct vergence response to the given disparities in the stimuli. In addition, only in 45.57% of the cases were the vergence response and the subjects' depth perception in agreement. These numbers alone indicate poor correlations

between recognition and eye-movements where eye-movements are, by far, more reliable in locating the stimulus.

This finding is further emphasized when we only consider the records wherein the subjects did not recognize the forms at all (about a third of the cases we recorded). In these cases 83.33% of the records have shown correct vergence response by the eyes while only in 2.08% of these stimuli did the subjects perceive the depth correctly.

More telling are the temporal factors. Averaging over all eye-movement records, it took the subjects, on average 5.05 seconds to recognize the forms in the RDS, whereas it took the eyes only 1.48 seconds to detect the contours of the forms and 1.51 seconds to make a correct vergence response. The difference in duration between the signs of detection and the event of recognition cannot be explained by a motor response delay caused by pushing the push-button. To elaborate further, when averaging all cases where the time for recognition was 3 seconds and longer, we found that it took on average 7.98 seconds for recognition but only 1.69 seconds to detect the contours and 1.82 seconds to make the correct vergence response. In the cases where the forms were not recognized at all by the subjects, the average time it took the eyes to detect the contours was 2.36 s. and 2.22 s. for correct vergence. The time for the eyes to detect the attribute of the presented forms is very small in comparison with the time that was required for form recognition.

This data strongly supports the notion that eye-movements do not correlate with cognition.

In addition, as we mentioned earlier, one of the subjects was stereo blind, and could not recognized the forms at all. However, his eyes tracked the attributes of the forms faithfully.

GENERAL DISCUSSION AND CONCLUSION

In summary, our two experimental protocols bear directly on relating external measures to visual cognition, in particular with a view to detecting signs of cognitive overload, fatigue or insufficiency.

- The study on eye-movements versus recognition in the case of random dot stereograms revealed the fact that visual cognition and eye-motion are not so coupled that one can be

related to the other even crudely. Appropriate eye motion, as if seeing an object, occurred often without any subjective experience of seeing it. Conversely, recognition of an object occurred well before the eyes moved to home on the contours. Since the goal is to assure that cognition serves delicate and appropriate task performance, it is evident from this work that eye motion does not suffice as a crude measure of visual cognition, much less a reliable one.

- More appropriate may be direct interactive measures that test an individual's particular visual strategy in the use at the moment. Since there are several such strategies that can be characterize in terms of the angular width and shape of the form-resolving field and the centering of that field with respect to the center of gaze, any measure which reveals an inappropriate strategy or the inflexibility of shifting to a different strategy, is more likely to be an index of cognitive overload or fatigue than any purely external measure. The FRF is the pre-cognitive setting of the distribution of lateral masking for the task at hand.

The problem of assessing blunted cognition involves addressing the cognition itself as inferred from task-performance rather from the use of any physical measure on the mechanism alone. As in neurology and psychology, external signs are unreliable until function is tested, in a direct way. Work reported here opens a new path to interactive tests that do not significantly interfere with the task being performed. These tests have already shown their value in diagnosis and treatment of dyslexia, a disorder that cannot be measured by external signs alone nor by tests that do not challenge the cognitive process directly.

It is the development of such carefully targeted methods that will occupy the work to be done here, now that the foundations have been laid.

POTENTIAL COGNITIVE AND METHODOLOGICAL TECHNIQUES FOR MEASURING COGNITIVE OVERLOAD

RESEARCH OBJECTIVES

- The intended scope of this research program was four-fold:
- Determine candidate techniques for measuring and analyzing ocular behavior as an index of cognitive workload under fatigue.
- Experimentally determine a relationship, if any, between ocular behavior and fatigue-induced performance decreases in tasks of human visual target detection and target tracking.

- Conceptually explore other physiological parameters related to fatigue or stress that correlate with ocular behavior.
- Provide a preliminary design specification for a cognitive workload measurement apparatus.

FULFILLING THE OBJECTIVES

Determining the Relationship Between Ocular Behavior and Diminished Task Performance

Our experimental protocols have made clear that eye movements, per se, cannot reflect cognition.

Hence, techniques for measuring and analyzing ocular behavior as an index of cognitive workload under fatigue must be task specific and pertain to the individual performing said task(s). The data processing technology for determining individual performance characteristics is state-of-the-art with today's 32 bit embedded microprocessor technology. Of interest is the nature of the sensors used to determine eye movements in a manner that is comfortable and does not interfere with the user's ability to perform the task.

Our findings can be summarized as follows:

- The continuous recording of eye movements is applicable only for tasks that depend upon the monitoring of tracking slow moving objects.
- Eye position (i.e., the determination of where the eyes are pointed) can be detected on a non-continuous basis for applications in which an artificial visual stimulus is imposed upon the visual task and eye position is detected in addition to the response or lack of response of the individual performing his task. In such, the eye-tracking sensor (e.g., an EOG) is turned on at the time the artificial stimulus is generated.
- Each visual strategy is specific to the task performed and the subject performing the task is well practiced.
- Norms must be established on an individual basis such that individual deviations that reflect fatigue or cognitive overload can be detected.

Physiological Measurement Methods

There are a number of established methods of measuring eye movements and eye position. They range from the elegantly simple electro-oculogram (EOG) to the complex infrared or video camera pupilometry.

EOGs consist of four miniature bipolar electrodes placed above, below and to each side of each eye. They detect the electrical potential generated by the dipole of the eye as it rotates in the socket. In addition to detecting the position and motion of each eye independently, stereoscopic binocular fixation can be determined by manually recorded techniques or by computer analysis. EOGs function irrespective of eyelid state, and eyelid status (open, shut or blinking) can be determined utilizing the same electrode used to measure EOG. The EOG is very useful, therefore, in determining eye motion during sleep and in establishing rapid eye motion (REM) sleep states.

EOG designs are subject to amplifier drift, and AC coupling techniques used to establish a consistent baseline undermine attempts to observe slow processes of eye drift.

Pupilometers are very exact in their measurement of eye position, providing the eye remains open. Pupilometers are very effective in counting eye blinks, and determine pupil size in addition to eye position. Pupil size and blinking rates might be useful in determining sleepiness and fatigue, and, thereby measure the decrease in visual-based performance.

Pupilometers are complex devices and are difficult to use in normal working applications, e.g., piloting and aircraft or monitoring a radar screen. They are usually bulky, expensive and require frequent adjustment. Recent advances in microprocessor technology, laser diode technology and ASIC (application specific integrated circuits) fabrication technologies might make possible the development of wearable pupilometers, however, the current demand for such technology does not justify the investment required to make such devices available for experimentation.

Time-domain measurements of respiration and cardiac rates have come into vogue in recent years and have been used to measure the ability of an individual to perform tasks under physiologically

stressful situations (Krasner, et al., 1979), as well as to indicate cardiovascular compensations to pathophysiological changes in physiological regulation (e.g., early warning of diabetic or vascular shock). In these situations cardiac rate is measured not only in the traditional beats-per-minute, but by the rate-of-change (derivative) of the time period between heartbeats.

It is known, for example, in diabetic hypoglycemia that although heart rate seldom exceeds 85 to 90 beats per minute, the normal sinus arrhythmia associated with respiration induced vagal stimulation gives way to chaotic changes in beat-to-beat intervals. It may be possible to determine if fatigue alters sinus beat-to-beat control of cardiac rate in some measurable fashion.

Preliminary Design Specification for a Cognitive Workload Measurement Apparatus

Following the results of our investigation, we provide an example of how transient measurement of ocular behavior might be used as an index of cognitive workload under normal and fatigued conditions.

The following represents a simplified prototype design for testing cognitive adequacy.

In many of the tasks, confronted by air controllers for example, a detailed and accurate account has to be made of small visual icons. As an example of testing the cognitive adequacy of a person at that task we suggest the following prototype procedure.

The task: An icon is presented on a screen. Its quality is abruptly changed by changing the color, contrast or sharpness of its boundary (not by moving it). The subject's task is to press a push-button as soon as a change in the icon occurs. These changes are made intermittently. While the subject attends the icon and presses the push-button whenever a change occurs, a letter is briefly flashed (say for 20 ms.) at about 10 deg. of visual angle to either the right or left side of the icon, the sideness randomly chosen. If the subject recognizes that letter, this indicates that the attention is wide and therefore not adequate in attending only to the icon. But if the letter was not seen by the subject, or it was detected by the subject as "something that was there" yet unclear what it was, that will imply that the subject's attention is narrow and pointed at the icon. The cognitive adequacy in this case depends on the ability of the subject to attend solely to the icon. If desired, task performance could be gauged to verify this notion by measuring the subject's reaction times to the change in the icon. The reaction time will be longer when the attention is wide and shorter

(signifying a better task performance) when the attention is only on the icon. This is one example of assessing attention and hence cognitive adequacy. The method can be incorporated in a multi-task situation.

This procedure could be done in a fraction of a second, and hence interfere little with the performance of the task itself. As many tasks involve and depend on "pointed attention" this prototype could serve as the test of cognitive adequacy while performing those tasks. However, as tasks differ on from another a careful and detailed design will have to be made for separate kinds of tasks.

There also are tasks where visual wide field has to be attended. In a similar way as above, letters (or other icons) could be presented in the center field. Their recognition would indicate narrow attention, or cognitive inadequacy for the task, as a wide attention was needed.

These prototypes are examples derived from the experimental data we present here in the report.

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FIGURES

Table 1, RDS general results

	A	B	C	D	E	F	G	H	I
1	**correlations [%] between:**						**Duration [sec.] from onset to:**		
2		**form &**	**disparity &**	**vergence**	**vergence &**			**detection by eys of:**	
3		**percept**	**depth perc..**	**& disparity**	**depth perc.**		**recognition**	**position**	**vergence**
4									
5	**Sum of all RDS records**								
6	n	158	158	158	158		158	101	158
7	sum	105	71	131	72				
8	average	**66.46**	**44.94**	**82.91**	**45.57**		**5.05**	**1.48**	**1.51**
9	SD						3.82	1.48	1.36
10									
11	**All RDS records, 3 s. or longer to recognize**								
12	n	84	84	84	84		84	35	84
13	sum	35	20	70	20				
14	average	**41.67**	**23.81**	**83.33**	**23.81**		**7.98**	**1.69**	**1.82**
15	SD						2.53	1.26	1.51
16									
17	**All RDS records, not recognized**								
18	n	48	48	48	48		48	11	48
19	sum	0	1	40	0				
20	average	**0.00**	**2.08**	**83.33**	**0.00**		**10.00**	**2.36**	**2.22**
21	SD						0.00	1.47	1.80
22									
23	**Data for the different forms**								
24	**Flats**								
25	n	57	57	57	57		57		57
26	sum	16	10	50	8				
27	average	**28.07**	**17.54**	**87.72**	**14.04**		**8.15**		**1.81**
28	SD						2.93		1.68
29									
30	**All single squares**								
31	n	66	66	66	66		66	66	66
32	sum	60	40	50	43				
33	average	**90.91**	**60.61**	**75.76**	**65.15**		**2.97**	**1.68**	**1.44**
34	SD						2.88	1.64	1.15
35	**Double Squares**								
36	n	13	13	13	13		13	13	13
37	sum	11	6	12	6				
38	average	**84.62**	**46.15**	**92.31**	**46.15**		**3.60**	**1.06**	**1.02**
39	SD						3.20	0.74	0.44
40	**Stairs (3)**								
41	n	11	11	11	11		11	11	11
42	sum	8	6	9	6				
43	average	**72.73**	**54.55**	**81.82**	**54.55**		**5.82**	**2.59**	**2.35**
44	SD						3.90	1.67	1.69
45	**Spirals**								
46	n	11	11	11	11		11	11	11
47	sum	10	9	10	9				
48	average	**90.91**	**81.82**	**90.91**	**81.82**		**2.90**	**0.88**	**0.99**
49	SD						2.93	0.56	0.75

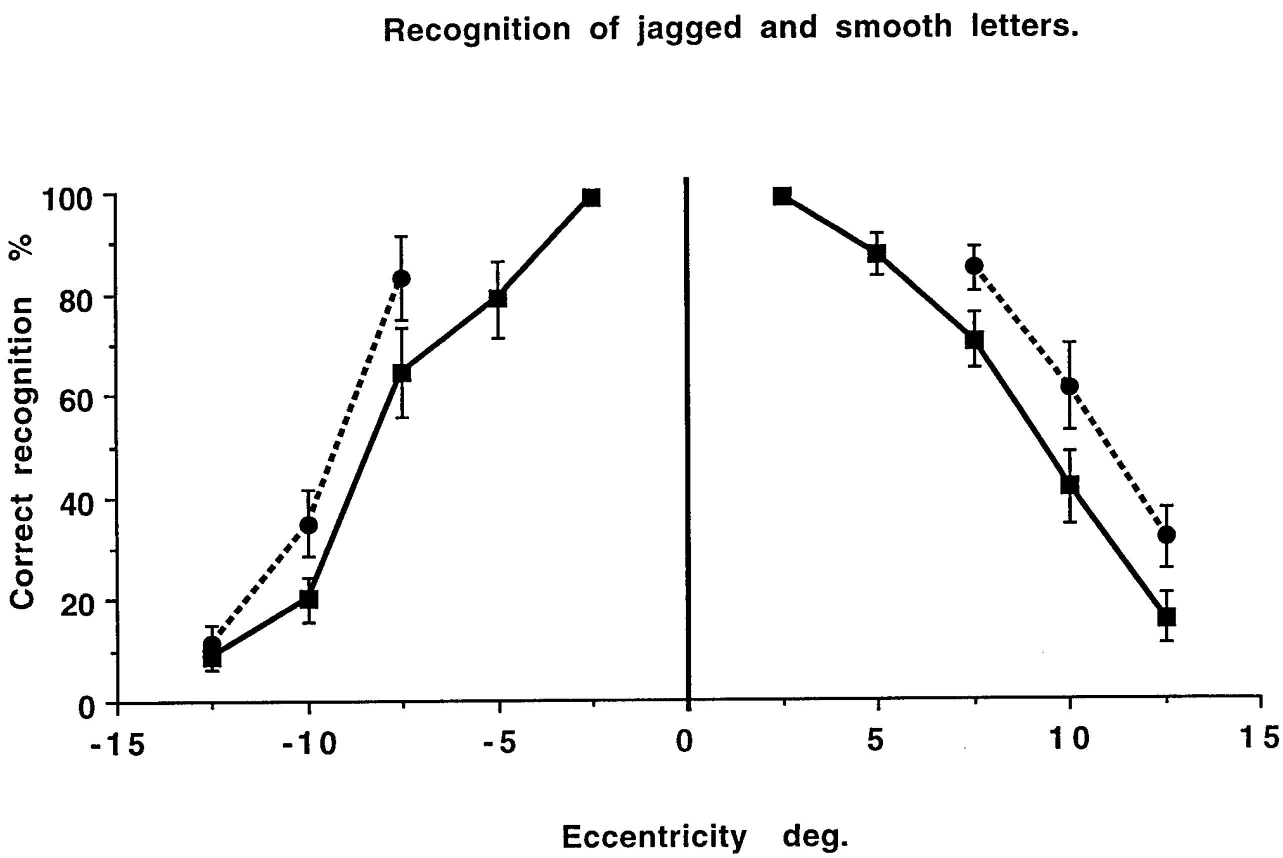


Figure 1. The average FRF measured with smooth (solid line) and jagged (dashed line) letters.

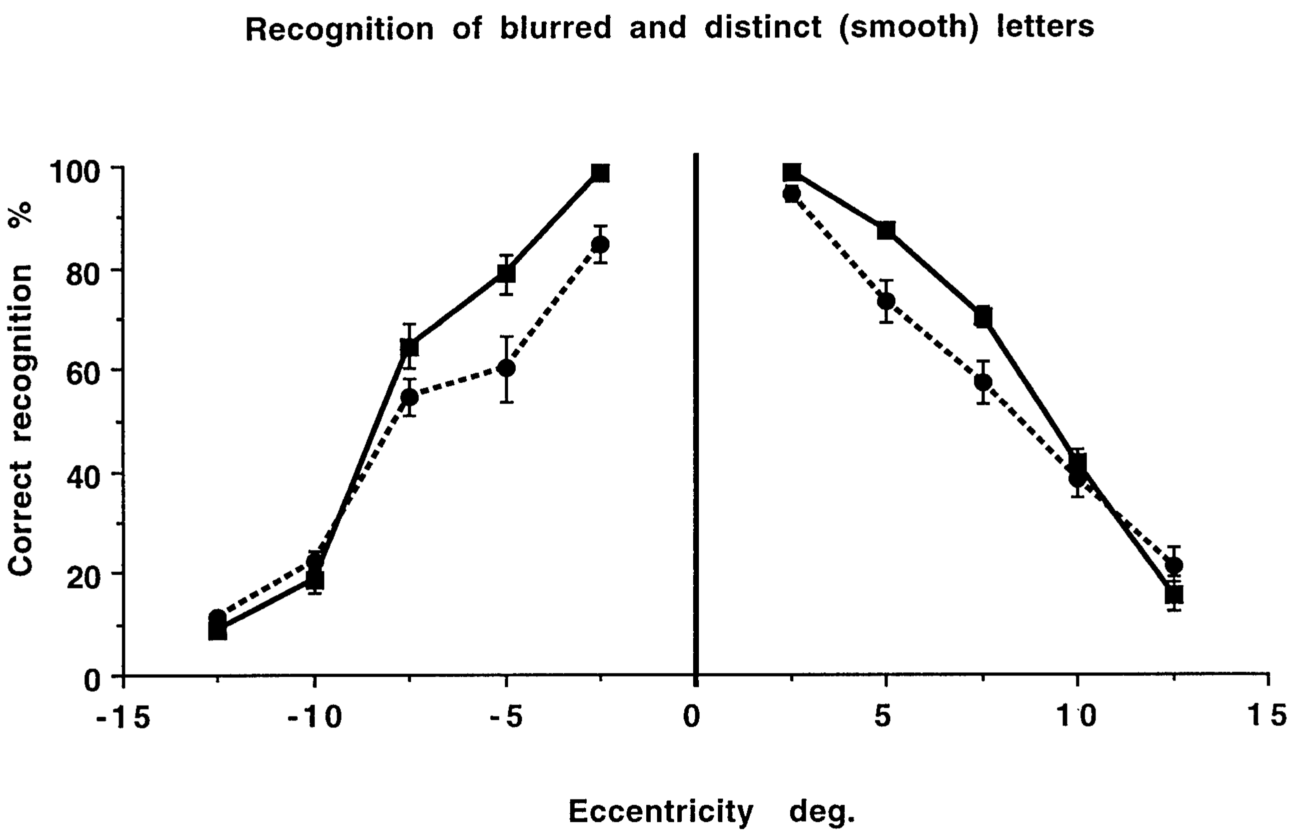


Figure 2. The average FRF measured with smooth letters. When distinct (solid line) and blurred (dashed line).

Figure 3. A demonstration of transition between two visual strategies. Gaze first at the print with in the frame and then move the gaze to the smooth writing below.

A demonstration of lateral masking

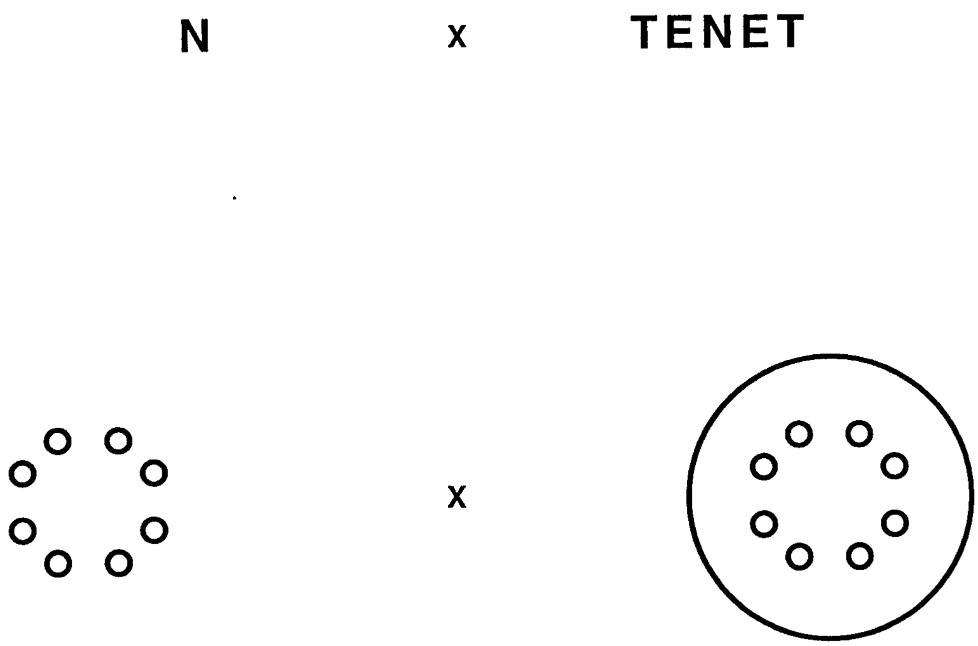


Figure 4. A demonstration of lateral masking. Fix your gaze on the upper x. Without shifting your gaze, the N on the left will appear clear and distinct whereas the N on the right will not be legible though segment lines will be clear. Similarly fix your gaze on the lower x. You will see small circles on both sides. Notice that on the left side there is a spatial arrangement of the small circles (a ring of circles?) while on the right the arrangement of small circle is lost.

X VSV

X VSV

Figure 5. Fix your gaze on one of the x's. Try to recognize the s on the right. All subjects asked recognize the jagged s easier.

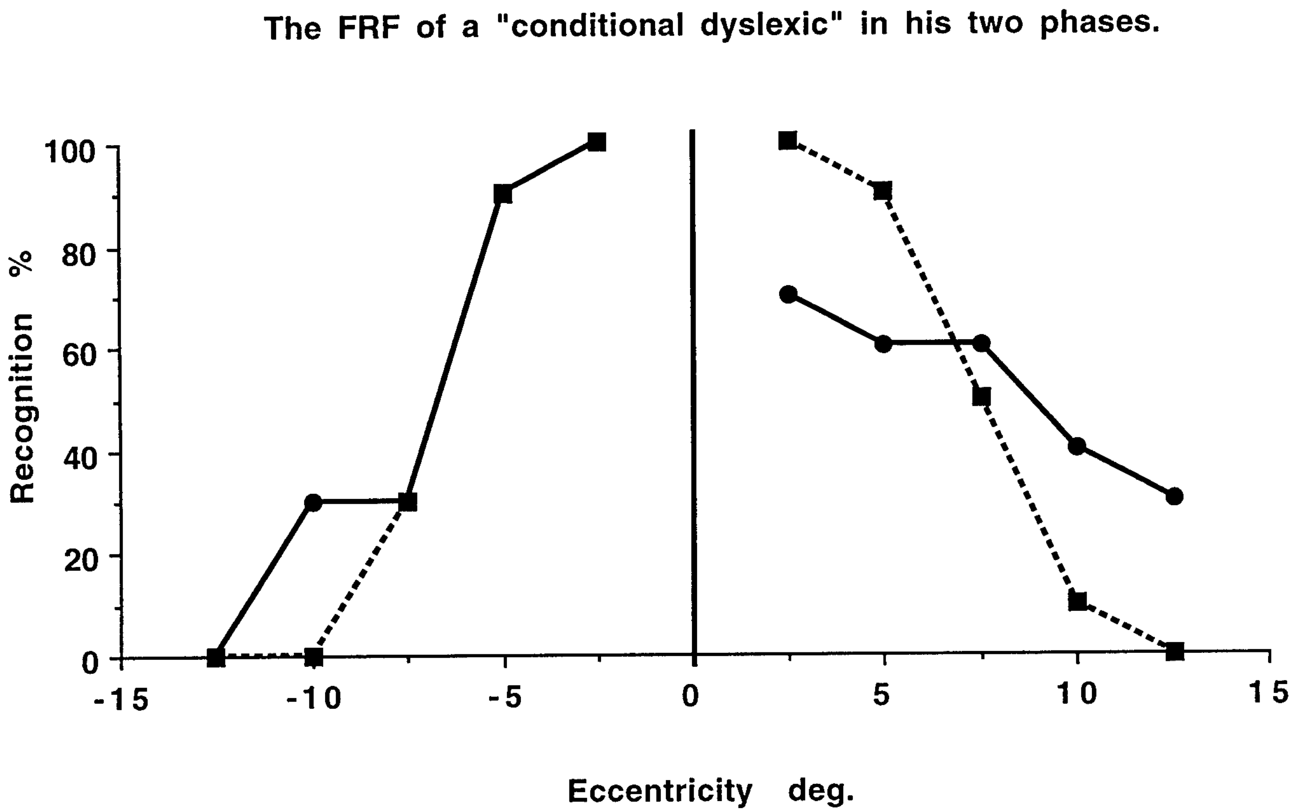


Figure 6. The FRF measured with a conditional dyslexic. The dashed line showe his FRF when he was in the alert phase and the solid line shows the FRF a few hours later, when he was “fatigued”.

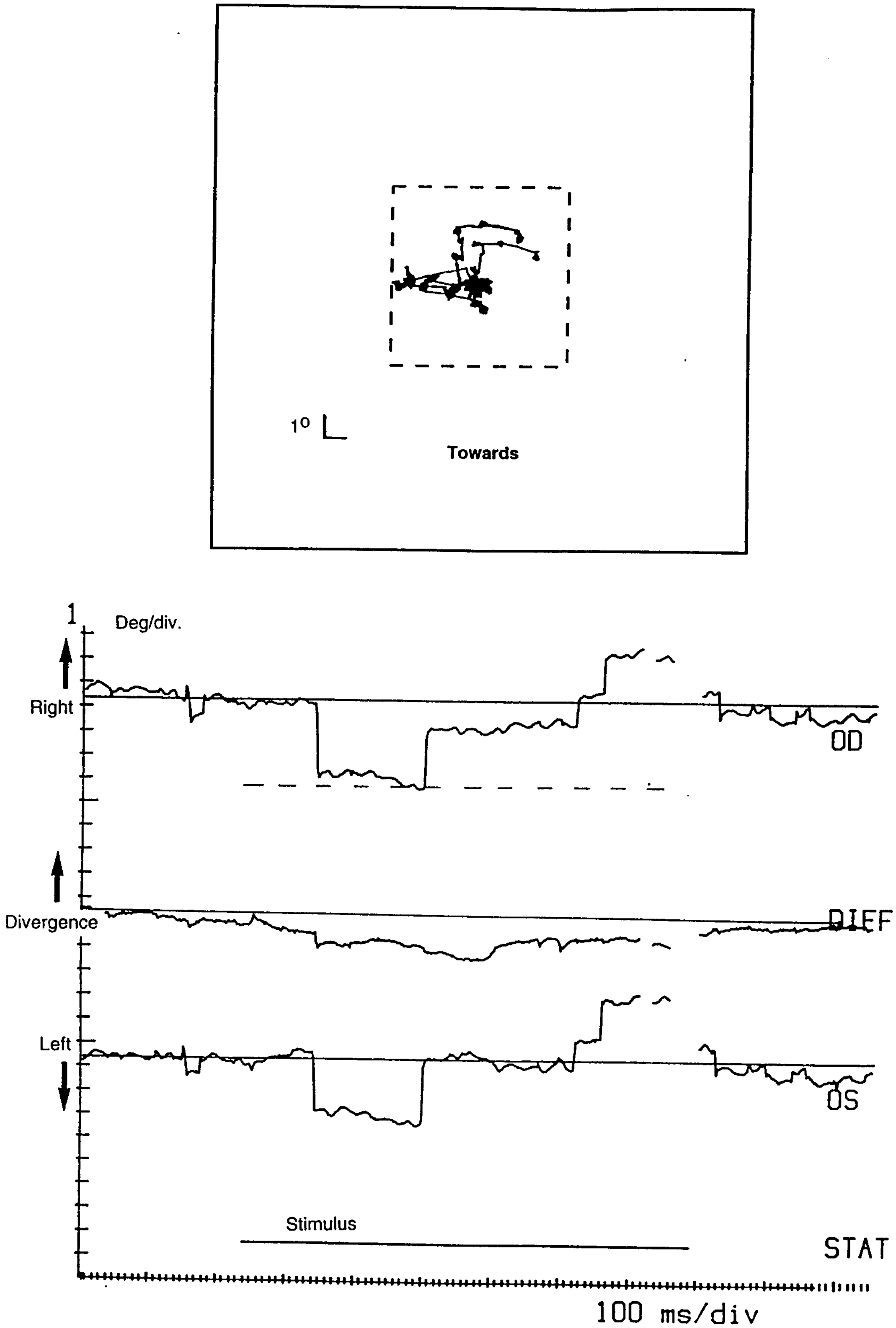
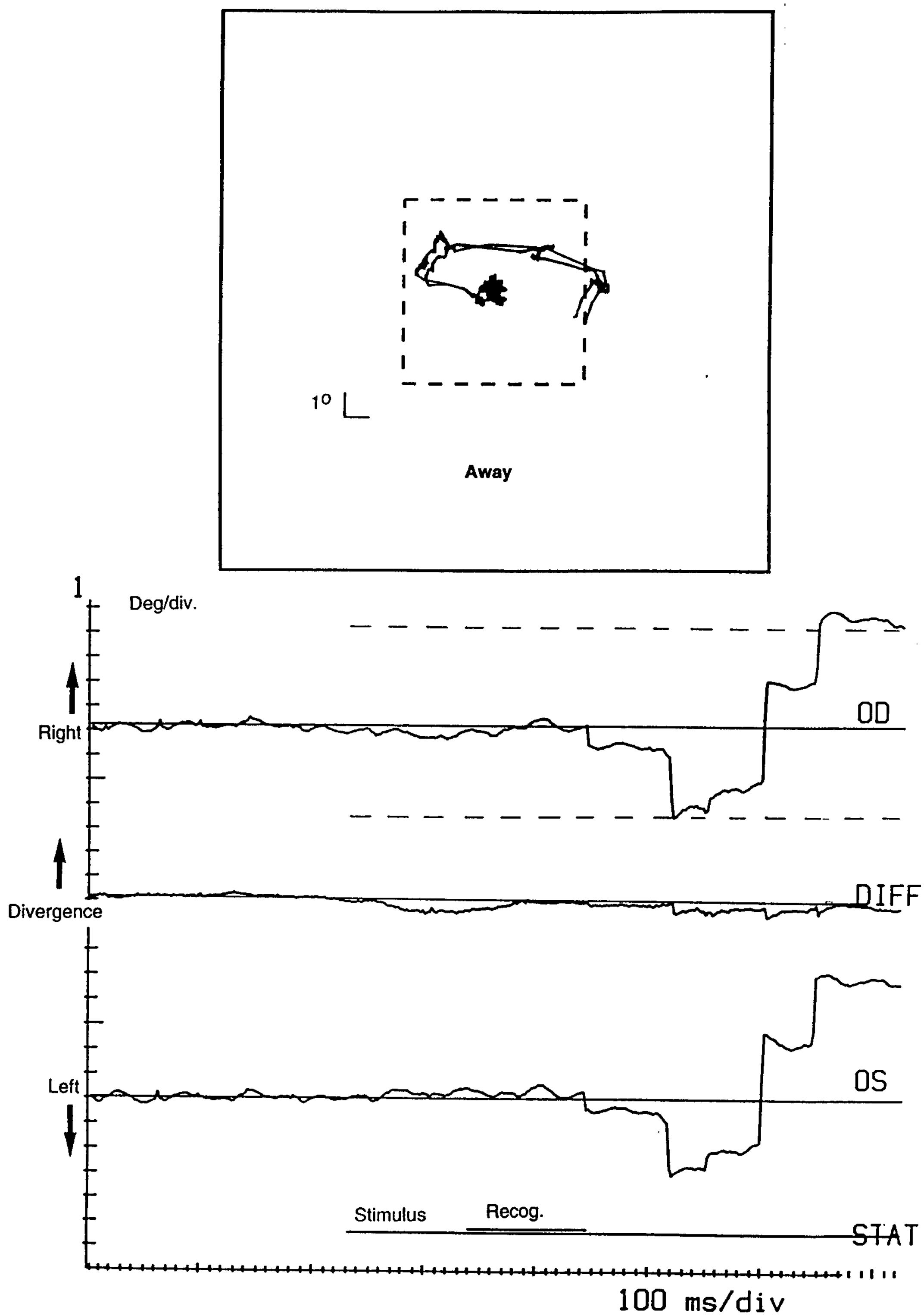


Figure 7. A single eye-movement record of a subject viewing a RDS stimulus with a square form (indicated by a dashed line, although the line does not appear in the stimulus). The top part is a 2-dimensional plot of the record. The lower is the horizontal eye-position record. The top trace is of the right eye, the lower of the left. The middle trace is of the difference between the position of the eyes. It measures the vergence response.



Figures 8. A single eye-movement record of a subject viewing a RDS stimulus with a square form (indicated by a dashed line, although the line does not appear in the stimulus). The top part is a 2-dimensional plot of the record. The lower is the horizontal eye-position record. The top trace is of the right eye, the lower of the left. The middle trace is of the difference between the position of the eyes. It measures the vergence response.

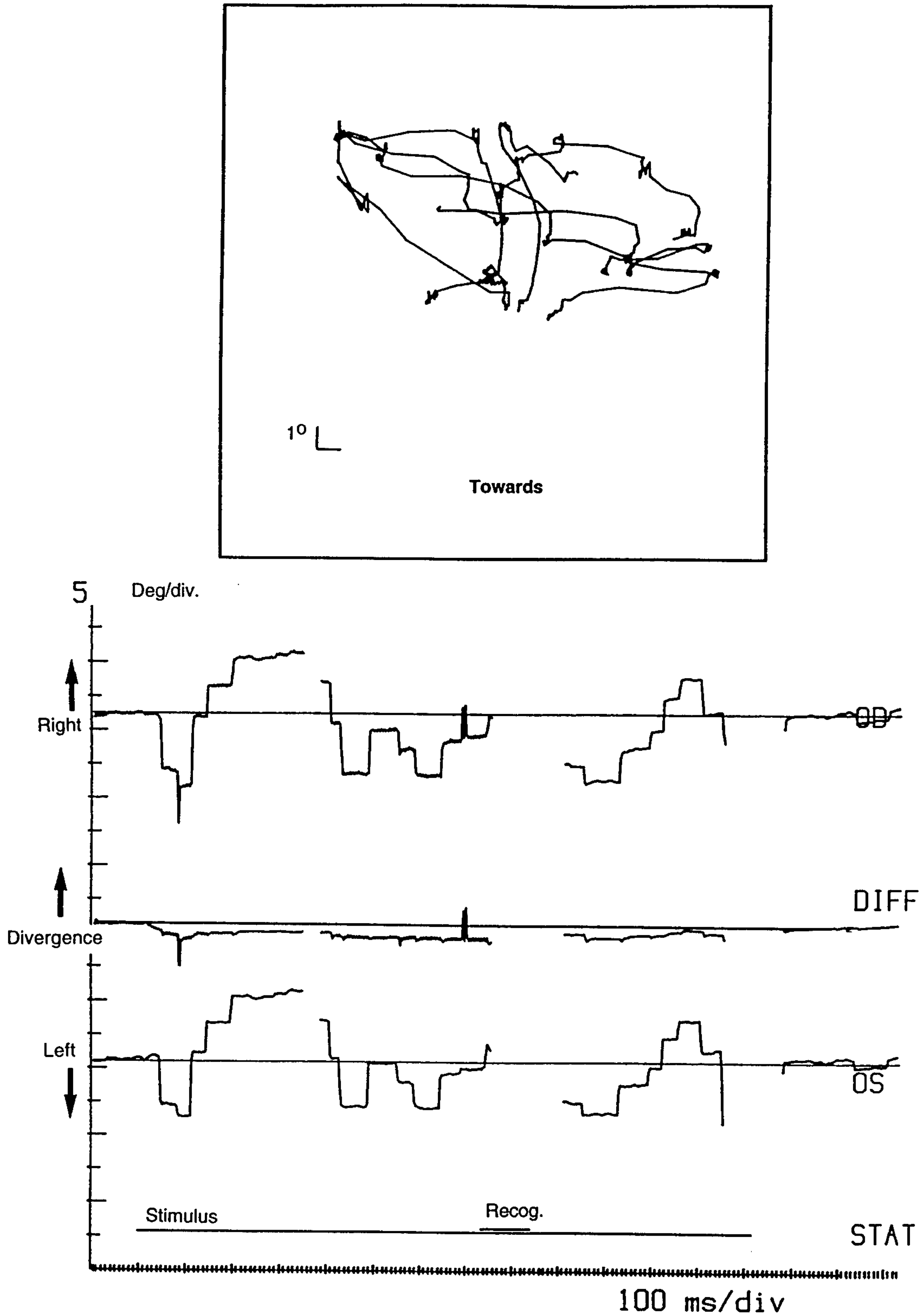


Figure 9. A single eye-movement record of a subject viewing a RDS stimulus with a flat plane (over the whole stimulus) pointing towards the subject. The top part is a 2-dimensional plot of the record. The lower is the horizontal eye-position record. The top trace is of the right eye, the lower of the left. The middle trace is of the difference between the position of the eyes. It measures the vergence response.

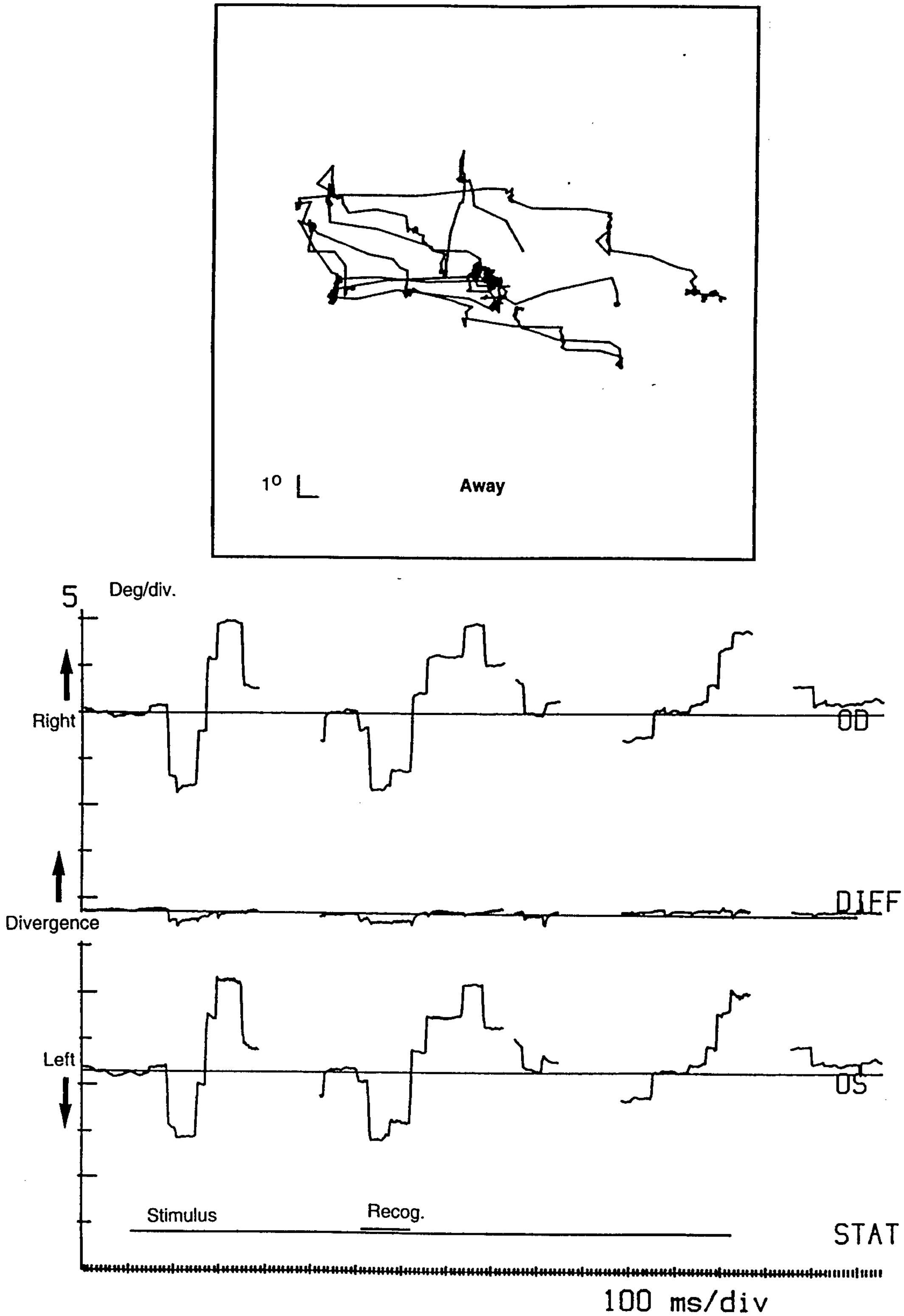
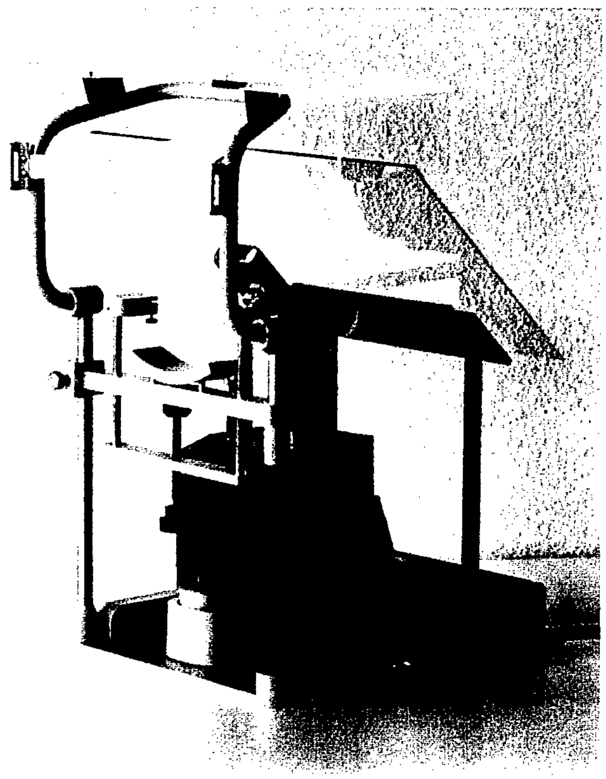


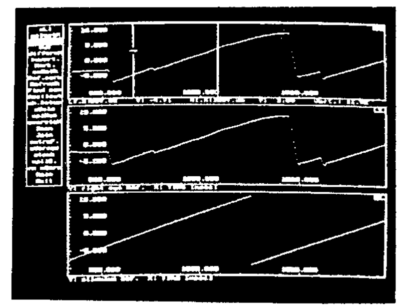
Figure 10. A single eye-movement record of a subject viewing a RDS stimulus with a flat plane (over the whole stimulus) pointing away from the subject. The top part is a 2-dimensional plot of the record. The lower is the horizontal eye-position record. The top trace is of the right eye, the lower of the left. The middle trace is of the difference between the position of the eyes. It measures the vergence response.

APPENDIX

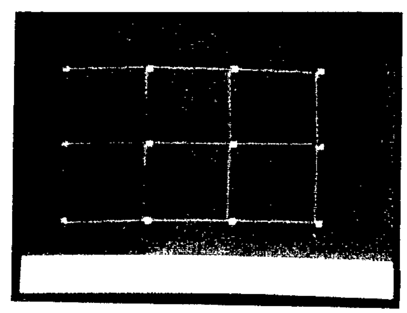
AMTech GmbH

ET3 EYE TRACKING SYSTEM



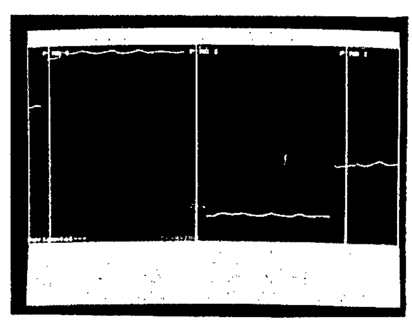


Detail from EYEMAP



Calibration Matrix

the AMTech ET3 is a fast, high resolution eye tracking unit that determines horizontal and vertical eye positions by using a high resolution linear CCD camera. This technology stands for up to 400 samples per second, high resolution, excellent linearity and no crosstalk between horizontal and vertical channels.
The ET3 also connects into a wide range of equipment for controlling and display of various stimuli; laser projector for slow pursuit, LED displays for any kind of saccade paradigms and video displays.
The ET3 software covers all needs from defining stimulus paradigms to saccades analysis, pursuit analysis and a sophisticated fixations analysis.



Detail from FIXATION

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ET3 SYSTEM COMPONENTS

Eye Tracking Unit:

horizontal,
vertical,
monocular and
binocular systems are available

fast, high resolution, excellent linearity,
can be used as pupilometer

Laser Target:

1 or 2 dimensional precision laser scanner including control card and software

LED Targets:

16 programmable digital signals for LEDs, buzzers, shutter etc.

Analog output:

output of data for on line display manipulation or chart recorder

Parallel port:

on line data transmission to display PC or other equipment

ET3 software provides :

- Stimulus generator:
  uses text files to make stimuli for LEDs, buzzer and Laser scanner
- Display program:
  (in preparation) uses list of PCX files and push button information to display scenes or text on display PC.
- Data acquisition:
  collects eye movement data and push button data
  controls stimulus,
  can transfer eye position to display computer,
- Data analysis:
  Analysis of saccades and pursuit -> EYEMAP
  Analysis of fixation -> FIXATION

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ET3 EYE TRACKING UNIT

The ET3 Eye Tracker is available from monocular, horizontal only to binocular , horizontal and vertical recording.

All systems are capable of pupilometrie.

SPECIFICATIONS

sampling frequency:

	horizontal	from 50 to 400 Hz
	+ vertical	from 50 to 200 Hz

range:

	horizontal	+/- 40 °
	vertical	+/- 8°

linear range:

	horizontal	+/- 15 °
	vertical	+/- 8°

resolution:

	horizontal	2 arcmin
	vertical	10 arcmin

trigonometrical corrections can expand the linear range to the full measuring range.

PRINCIPLES OF OPERATION

The eye is illuminated by infrared light (880nm). It is them imaged on to a linear array of 1728 photo diodes (CCD-line camera) by means of a dichroic mirror, transparent for visible light yet reflective for infrared light, and a lens.

The CCD array of photo diodes is only 13 microns high and therefore puts a very thin line trough the image of the eye i.e. the pupil. The CCD produces a video signal that contains the exact position of the pupil margins. This position is transferred to a PC for storage and further calculations. As the position of both pupil margins is know, it also possible to calculate the diameter of the pupil precisely.

The vertical component of the eye position is determined by placing two measuring lines across the image of the eye. For this purpose the image is shifted up and down by a galvanometer mirror alternatingly. The vertical position can thus be calculated from two consecutive data sets, representing 4 positions on the circle of the pupil. These data are computed on line , allowing the mirror to track the movement of the pupil.

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ET3 TARGETS AND STIMULI

Hardware:

our 2D LASER SYSTEM controls
- 2 precision mirror drives that show a
- repeatability of 0.04 degree over a
- range of 40 degrees (can be extended to 80 degrees).

The mirrors move between two points within 1-2 milliseconds.

The high speed of the mirror drives extends the range of the laser stimulus from smooth pursuit to saccade stimulation.

A PC board controls
- two 12-bit D/A converters that provide the signals for the mirror drives.
- A high output frequency from the PC (up to 5 KHz) to the D/A converters produce a very smooth pursuit target even at high pursuit speeds.

Our new laser system will be equipped with a 680 nm Laser diode, that can be switched by one of the digital lines.

The PC board also contains
- 16 digital lines that can drive
  LEDs, buzzers or shutters, each line independently.

A set of push buttons can be connected to the eye tracker and to the printer port of a display PC. The status of up to for buttons is also registered.

Software:

The software that comes with this hardware uses a text file that contains wave forms, amplitudes frequencies, durations etc. that describe the stimulus in detail.
These text files are transformed to a file that can be used by the acquisition program. All stimulus data are being stored with the eye movement data.

A lookup file contains the information about which LED or LED combination corresponds to which point in space.

Software for PC display of the calibration targets with push button control is already available.

We currently prepare a program that also displays on a PC screen PCX files from a file list. The pictures appear according to the push button input.
As the push buttons are also connected to the eye tracker perfect synchronisataion of display and data acquisition is maintained.

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ET3 EYE MOVEMENT ANALYSIS

EYEMAP

Software for Eye Movement Analysis

EYEMAP is a program for display and analysis of eye movements especially for analysis of saccades and smooth pursuit.

Using the pull down menus with the mouse it is easy to move through the different features of the program.

The mouse easily sets graphical cursors in the eye movement curves for zooming or manual measurements.

A context sensitive HELP function keeps the user informed about all features and about the current task.

Several users of the same program can have different PERSONAL SET-UPS of parameters for :
- graphics,
- analysis,
- paths and directories for data and results for fast and comfortable access to the data.

Saccades:

can be analysed automatically, semi-automatically and manually. Semi automatic evaluation suggests a saccade and displays saccade, velocity and stimulus around the saccade. It allows the user to correct the points of start and end of each saccade and also to correct the stimulus change that belongs to a saccade if necessary.

The program calculates:
start position, amplitude, peak velocity, duration, latency, peak acceleration, number of saccade after a certain stimulus change, stimulus amplitude and gain, in cases of smooth pursuit it calculates the stimulus velocity and stimulus position at the start of the saccade.

Smooth Pursuit:

The program can calculate RMS between eye movement and stimulus, GAIN of velocity and position.
For good velocity gain the saccades can be eliminated.
The curves can be interpolated after the saccades have been eliminated.

Several other features are available: Differentiating, Filtering, Zoom....

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ET3 FIXATION ANALYSIS

FIXATION:

This program defines and analysis fixations

CALIBRATION:

For reliable data analysis we use a grid of calibration points on the screen. This provides for local linear calibration within each filed of the grid. Tilts or minor nonlinearities are thus being eliminated. A sophisticated display shows the result of the calibration and helps to select calibration points. The calibration allows to make all further calculations in display units (i.e. pixels on the screen)

Fixation definition:

Fixations are defined as valid data during which the moved below a certain speed. Blinks are detected separately. The speed threshold and the minimal duration of a fixation are defined in the setup.

Analysis:

INTERVAL ANALYSIS:
The push button data may be used to define eye position during a defined Interval after the push button was pressed over a certain period. This feature may be used to check calibration and data validity. Delays and Interval length can be determined in the setup.

FIXATION ANALYSIS:
It uses the saccade/blink information to define fixations. Fixations may be "started" or terminated by push buttons as well. Even a delay after the button was pushed is possible.
Average values for horizontal and vertical eye position are calculated together with their standard deviation.
Size and other saccade parameters for the incoming and outgoing saccades are determined.
Due to the definition of "page" and "response" keys the number of the fixation on the current page can also be calculated as well as the current page number or response key number.
Several error codes define how a fixation was terminated (e.g. by blink, by push button ..)
All fixation are being displayed on a colour screen an can be accepted or rejected (i.e. store them anyway, but produce an error code). They may also be marked with a number for statistical analysis of special fixations.

Merging of data (preliminary):

In a second step the results of the fixation analysis will be merged with 'Object' information i.e. data about the size and position of objects on the screen.

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